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An active aerial element for h.f./m.f. receiving arrays

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AN ACTIVE AERIAL ELEMENT FOR H.F./M.F. RECEIVING ARRAYS

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Summary

A high-input-impedance amplifier has been developed which, when placed at the base of a short monopole, forms an active aerial element. This active aerial may be used as an element in a directional high- or medium-frequency receiving array using electronic steering. An important feature of the aerial amplifier is its high linearity which retains good performance in the presence of high interfering fields.

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AN ACTIVE AERIAL ELEMENT FOR H.F./M.F. RECEIVING ARRAYS

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1. Introduction

Electronically steerable active receiving arrays are being investigated for use in reception in the high frequency (h.f.) band for re-broadcasting purposes at oversea sites and also for monitoring services in the m.f. and h.f. bands. Arrays of this type have an advantage over a fixed array in that the main beam may be steered to receive the strongest signal from a wanted station. Another possibility being considered is the use of a steerable null in the directional array pattern. This could be used to reduce co-channel interference or the effects of another unwanted mode of propagation.

The output from each element in a conventional array not only comprises the energy received from the incident wave but also energy re-radiated from other elements. This re-radiation greatly complicates the design of conventional arrays, and in general it becomes difficult to obtain the desired radiation pattern and to control and adapt it in a predictable fashion.

The effects of re-radiation can be made negligible by using active receiving elements. If a short monopole is used with a very high impedance at its base then the re-radiation is very small. This can be achieved in practice by putting a high-input-impedance amplifier directly at the base of each monopole. Using this as an active element, a receiving array can be built with a predictable radiation pattern. Indeed, such an active element is probably essential if an electronically steerable array is to be a practical proposition.

2. General design considerations

2.1. Length of monopole

The active aerial is required to operate from 150 kHz to 30 MHz. It is desirable that the vertical radiation pattern* of the active aerial should remain substantially constant over this range. Therefore at the highest frequency (30 MHz) the monopole must not be greater than $\lambda/4$ in height, i.e. 2·5 m.

2.2. Amplifier input impedance

The aerial element has to operate over a very wide range of frequencies (150 kHz to 30 MHz) and is required to have as high an input impedance as possible. The reasons are twofold.

Firstly, at low frequencies the monopole has an extremely high impedance ($2 \times 10^{-4} - j5 \times 10^{3}\,\Omega$ at 150 kHz) and for good sensitivity, the amplifier must have as high an input impedance as possible, at least of comparable magnitude.

Secondly, at high frequencies, the mutual impedance between closely spaced elements becomes significant. To control the radiation pattern of a receiving aerial array it is necessary to control the relative amplitudes and phases of the contributions from each element. Because of the mutual impedance between two elements there is an induced e.m.f. in one, which is proportional to the current flowing in the other. This induced e.m.f. can be regarded as being due to re-radiation of energy from the elements; it will affect the respective contribution of each element and hence the radiation pattern. Reducing the element currents by means of a high-impedance amplifier reduces the induced e.m.f. whilst the directly received signal e.m.f. is unaltered. The outputs from all the array elements can then be added

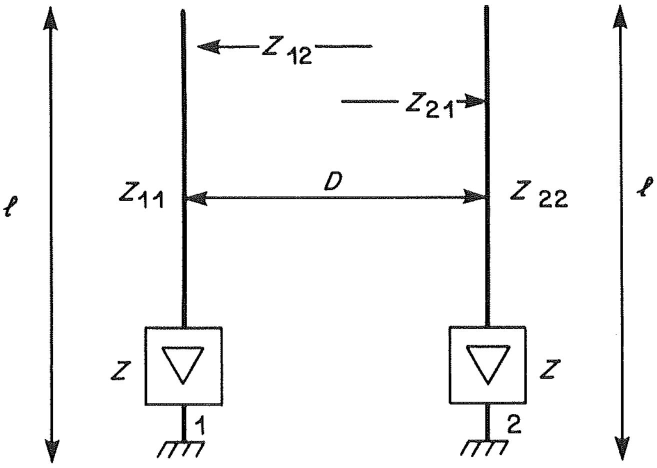

Fig. 1 - Diagram of two element active array

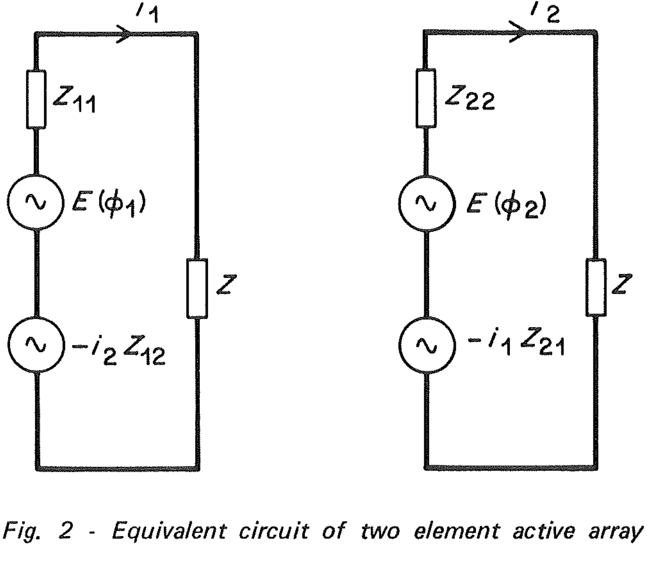

Fig. 2 - Equivalent circuit of two element active array

in the proportions required for a given array pattern without the need to allow for the mutual impedances. To show the effect of a high input impedance a simple two-element array is considered.

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* Although a receiving array is being considered it is convenient to use the term 'radiation pattern' when referring to the directional properties.

Fig. 1 shows two active elements, length l, spaced distance D apart, the equivalent circuit is shown in Fig. 2. The amplifier input impedance is Z and the monopole self impedances Z_{11} and Z_{22}. Z_{12} and Z_{21} are the mutual impedances between the two elements.

The e.m.f. induced in each element due to an incident wave is $e(\phi_1)$ and $e(\phi_2)$. The element currents are i_1 and i_2 and the resulting e.m.f. in each element due to mutual impedance is $-i_2Z_{12}$ and $-i_1Z_{21}$. The relationship between currents and voltages in the circuits may be written in matrix form.

$$[V]=[Z]\,[i] \tag{1}$$

$$\begin{bmatrix} e(\phi_1)-i_1Z \\ e(\phi_2)-i_2Z \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{2}$$

Re-arranging gives:

$$\begin{bmatrix} e(\phi_1) \\ e(\phi_2) \end{bmatrix} = \begin{bmatrix} Z_{11}+Z & Z_{12} \\ Z_{21} & Z_{22}+Z \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{3}$$

If, at the highest operating frequency $l \simeq \lambda/4$ (resonant monopole) and $D = \lambda/4$ then the following values apply for the Z matrix assuming ideal thin-wire elements.[3]

$$Z_{11} = Z_{22} = 35 + \mathrm{j}0\ \Omega \tag{4}$$

$$Z_{21} = Z_{12} = 20{\cdot}4 - \mathrm{j}14{\cdot}2\ \Omega \tag{5}$$

$$\begin{bmatrix} e(\phi_1) \\ e(\phi_2) \end{bmatrix} = \begin{bmatrix} 35+Z & 20{\cdot}4-\mathrm{j}14{\cdot}2 \\ 20{\cdot}4-\mathrm{j}14{\cdot}2 & 35+Z \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{6}$$

i_1Z and i_2Z correspond to the input voltages to the amplifiers – these will be effectively independent of each other if the Z matrix can be regarded as a diagonal matrix. This will occur if the values of Z in the matrix (6) are much larger than any of the other values.

Thus in the limit

$$e(\phi_1) = Z\,i_1 \tag{7}$$

$$e(\phi_2) = Z\,i_2 \tag{8}$$

As a convenient example for $Z = 965\Omega$ Equation (6) becomes

$$\begin{bmatrix} e(\phi_1) \\ e(\phi_2) \end{bmatrix} = \begin{bmatrix} 1000 & 20{\cdot}4-\mathrm{j}14{\cdot}2 \\ 20{\cdot}4-\mathrm{j}14{\cdot}2 & 1000 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{9}$$

Solving for i_1

$$i_1 = \frac{e(\phi_1) \times 1000 - e(\phi_2) \times (20{\cdot}4 - \mathrm{j}14{\cdot}2)}{10^6 + \mathrm{j}579} \tag{10}$$

and $|e(\phi_1)| = |e(\phi_2)|$ because element lengths are equal.

For different angles of arrival of signal, the phases of (ϕ_1) and (ϕ_2) will vary, giving a possible amplitude error of about 0·2 dB and possible phase error of ±1½°.

As a contrast, consider the effect of mutual impedance when the two elements have 50Ω loading to earth

$$i_1 = \frac{e(\phi_1) \times 85 - e(\phi_2)\,(20{\cdot}4 - \mathrm{j}14{\cdot}2)}{7{,}010 + \mathrm{j}579} \tag{11}$$

The possible amplitude and phase error in this case are up to 2·9 dB and ±15° depending on angle of arrival of the signal.

An input impedance of about 1 kΩ is probably as high as can be achieved bearing in mind that the input cannot be tuned. The expected values of phase and amplitude error calculated from Equation (10) are considered sufficiently small for most practical purposes.

2.3. Amplifier linearity

The aerial amplifier must be highly linear if the aerial is to be used for receiving weak signals in the presence of strong unwanted signals. The problem can arise at m.f. and h.f. receiving sites near h.f. transmitting stations and even at relatively long distances from powerful m.f. stations. Cross-modulation and intermodulation products from the strong signals will interfere with the weak wanted signal. The radiation pattern of the array cannot be used to discriminate against the source of this interference because the non-linear effects occur within each omnidirectional receiving element.

Monitoring stations in the U.K. may be required to receive signals as low as 1μV/m, yet many of these sites have fields of the order of 20 mV/m from domestic m.f. stations. These signals would typically give signal levels of −112 dBm and −26 dBm respectively at the output of the active aerial if it were matched into a 50Ω system. For input levels of this order non-linear products must be very much less than −86 dB below the strong signal if the 1μV/m signal is to be receivable.

2.4. Noise

External noise levels in the m.f. and h.f. bands are generally very much greater than thermal noise.[1] A typical curve is shown in Fig. 3. This shows that the noise generated by the equipment is not particularly critical.

It is difficult to define the noise factor of an active aerial because of the variation of the impedance of the monopole with frequency. However, it is possible to

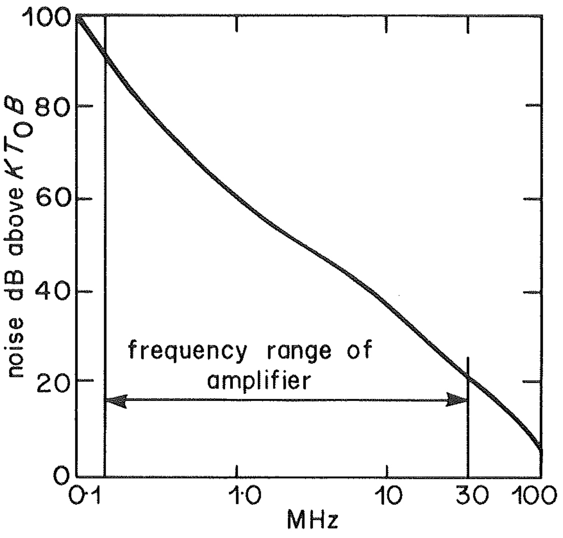

Fig. 3 - Atmospheric, man made and galactic noise over the l.f., m.f. and h.f. bands

measure the noise power at the output of the amplifier at a given frequency when the input has an impedance across it equivalent to the monopole. The output noise factor can then be defined as[2]

$$\text{output noise factor} = \frac{\text{Noise power out of active aerial}}{\text{Thermal noise power}}$$

2.5. Frequency response

When driven from a low source impedance the frequency response of the amplifier should be flat from 150 kHz to 30 MHz. When the amplifier is driven from a source with varying impedance, such as a monopole, the input impedance of the amplifier will govern the frequency response.

2.6. Additional requirements

Two further requirements of the active aerial amplifiers are that it should be relatively simple, cheap and require moderate d.c. power. These requirements are particularly important if a large array is to be built.

3. Development of the amplifier

The main criterion used in the design of the amplifier was very good linearity. Several amplifier configurations were built and tested, the most promising results were achieved with circuits of the form shown in Fig. 4. The output stage of this circuit (enclosed in dotted lines in Fig. 4) uses two pairs of PNP/NPN complementary transistors to make a quasi-balanced configuration. This balanced arrangement reduces even-order non-linear products.

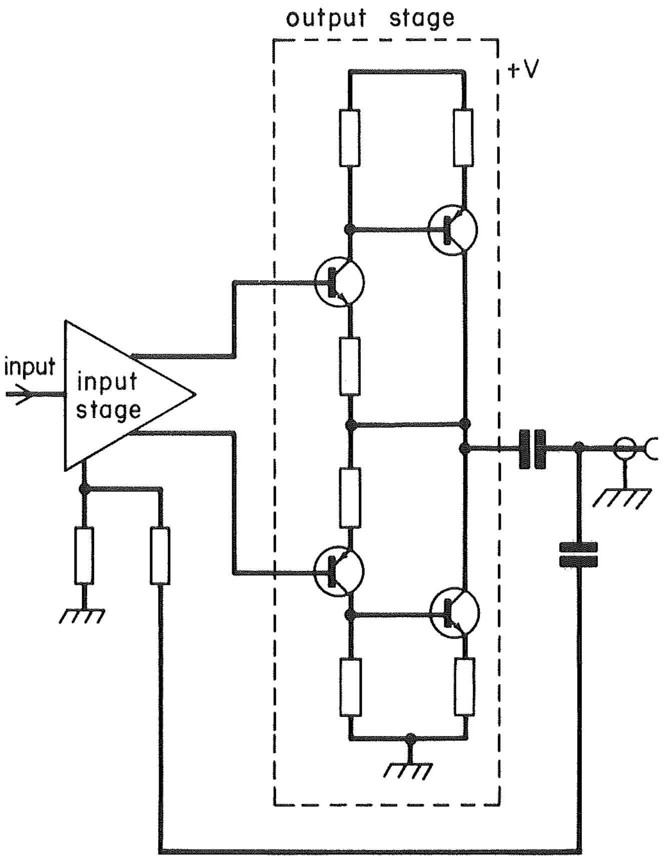

Fig. 4 - Initial amplifier configuration with overall feedback

This amplifier was unsatisfactory, however, for two reasons. It was possible to achieve good linearity, but only at spot frequencies with careful adjustment of the feedback. The linearity measurements were often not repeatable and the circuit needed constant readjustment. Secondly there

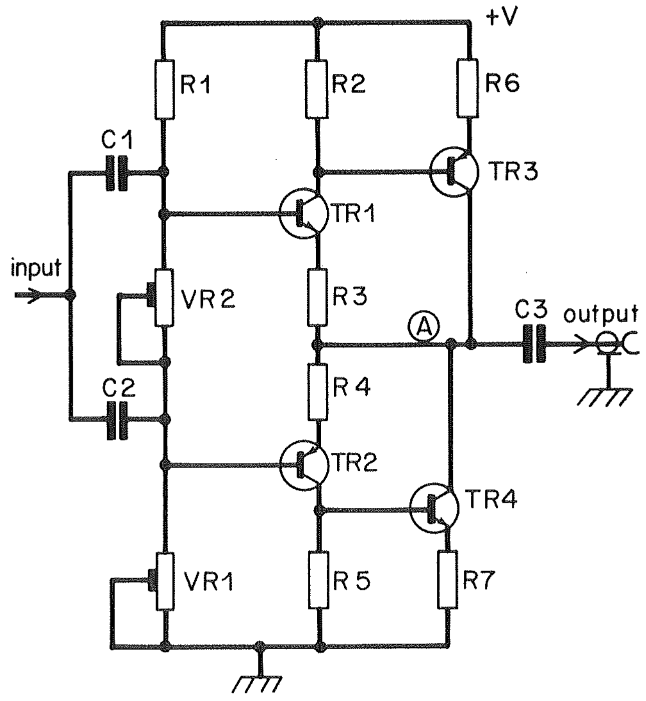

Fig. 5 - Output stage of aerial amplifier (distribution amplifier)

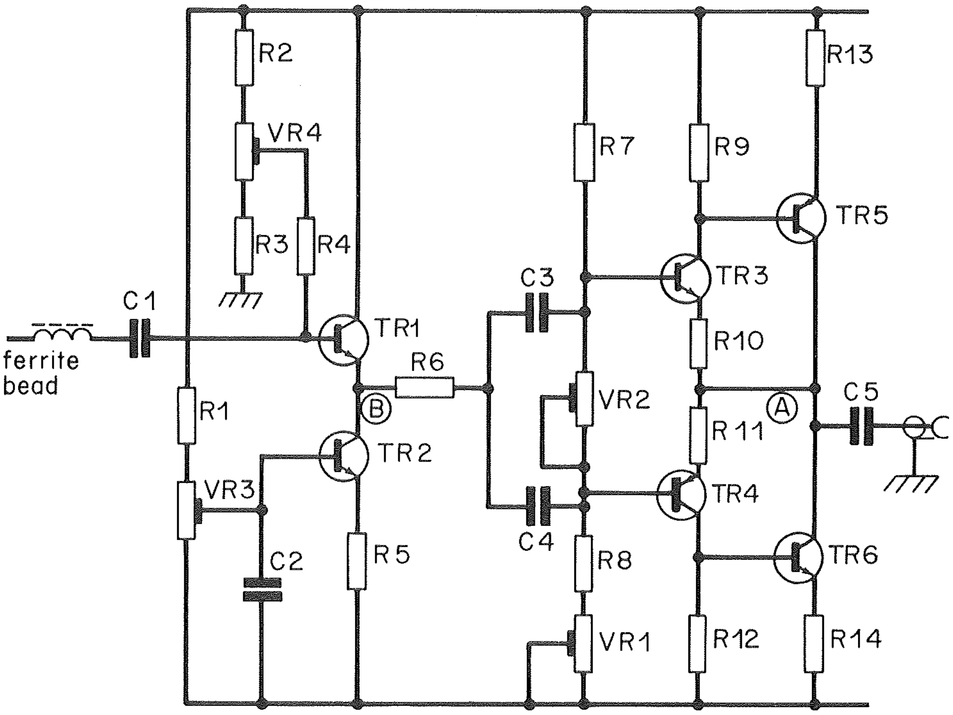

Fig. 6 - Complete aerial amplifier circuit

were problems of stability, particularly with variations in the input and output loading of the amplifier.

Good linearity and stability were achieved when the output stage was used on its own. The circuit of this amplifier is shown in Fig. 5. Two variable controls were added; VR1 adjusts the voltage at point A and VR2 controls the current flowing through the amplifier. By adjusting VR1 it is possible to minimize the even-order products. Adjustment of VR2 allows the odd-order products to be minimized.

The input impedance of this amplifier was found to be low, about $-j300\Omega$ at 30 MHz; this is too low to be coupled directly to a monopole. An emitter follower with a constant current source in the emitter circuit was used to buffer the output stage. This improved the situation, the input impedance being about $-j1000\Omega$.

The complete amplifier is shown in Fig. 6. It has good linearity provided the four variable resistors are correctly adjusted. VR1 and VR2 are as described previously. VR3 adjusts the current flowing through the input stage and VR4 controls the voltage at point B. These two controls are to some extent interactive, both have to be adjusted for best overall linearity.

Although the output stage alone was not suitable for the active aerial amplifier, it can be used as a distribution amplifier for use in active arrays. Therefore results for this amplifier are also tabulated in the next section.

4. Measured performance of the amplifiers

4.1. Input impedance

The input admittance of the amplifier was measured

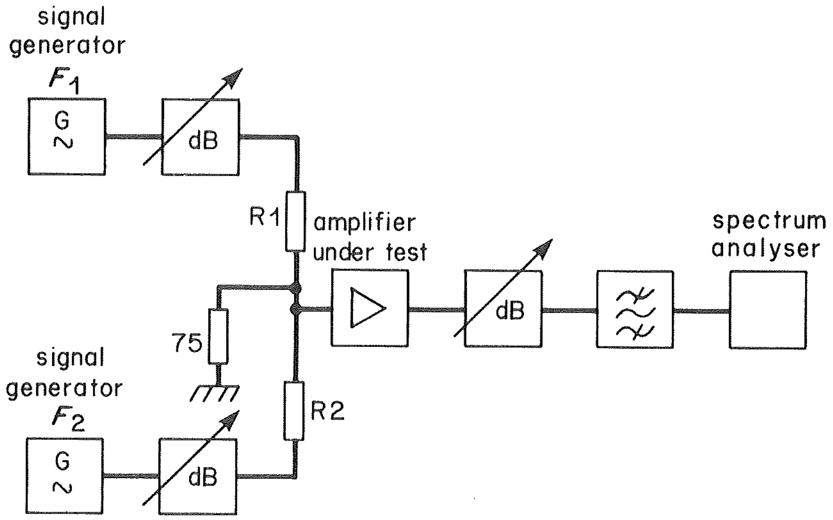

Fig. 7 - Linearity test arrangement

using a v.h.f. admittance bridge. The input impedance of the aerial amplifier at 30 MHz is 56 – j1060Ω and that of the distribution amplifier is 8 – j295Ω. Both these measurements were made after the bias controls had been set for best linearity.

4.2. Linearity

Measurement of linearity by observing harmonic distortion is prone to error due to the levels of harmonics produced by all signal generators. Intermodulation distortion can be measured more reliably and a 'two tone test' was used to measure the linearity of the amplifiers. The arrangement used is shown in Fig. 7. The two signal generators were both capable of supplying about 5 V r.m.s. signal, therefore R2 and R1 were made large (350 and 750Ω respectively) so that cross coupling between generators was reduced. The level of intermodulation products produced by adding the signals together in this way was −120 dB below an output voltage of 0·5 V r.m.s. at the input of the amplifier.

The two signals intermodulated in the amplifier and produced intermodulation products (i.p.'s). The amplifier was followed by a band pass filter which allowed the i.p. being measured to be passed to the spectrum analyser and

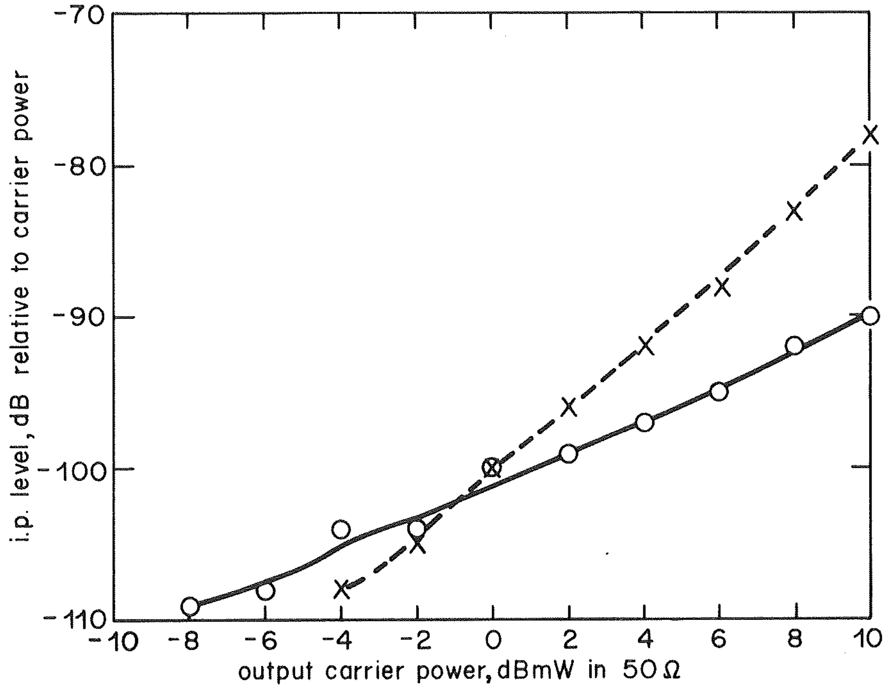

Fig. 8 - Result of two tone test on distribution amplifier

O——O 2nd order
X– – – –X 3rd order

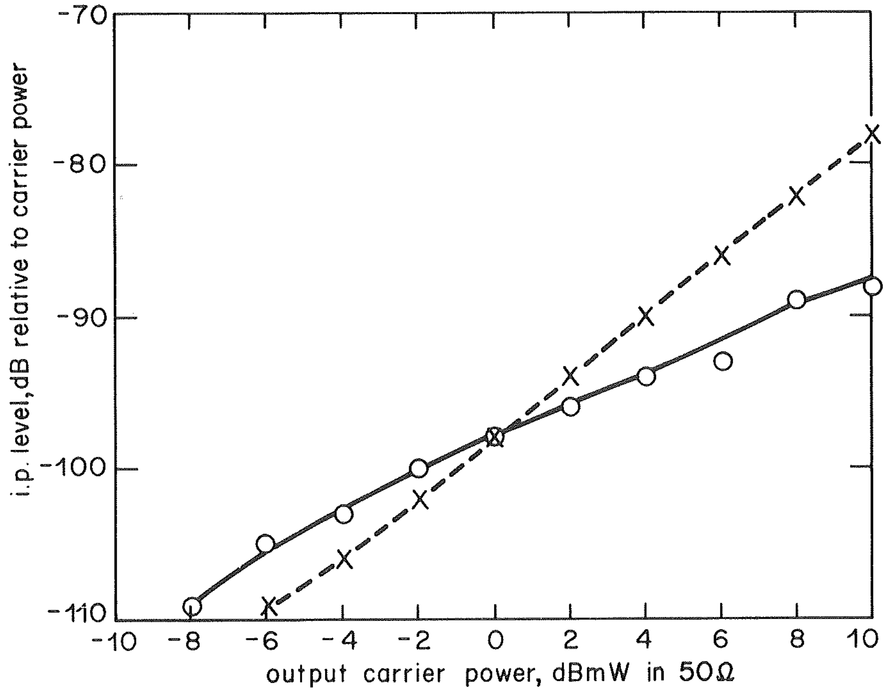

Fig. 9 - Result of two tone test on aerial amplifier

O——O 2nd order
X– – –X 3rd order

prevented intermodulation taking place in the analyser itself.

The frequencies of the two generators f_1 and f_2 were chosen so that the i.p. being measured fell within the pass-band of the filter. Measurement was confined to second-order ($f_1 + f_2$ etc.) and third-order ($2f_1 - f_2$ etc.) i.p.s.

Figs. 8 and 9 show the results of the two tone test on the distribution and aerial amplifiers respectively. The filter used for these tests had a pass band of 150 kHz centred on 10·7 MHz. In the second order test f_1 = 6·4 MHz and f_2 = 4·3 MHz and in the third order test f_1 = 7·5 MHz and f_2 = 4·3 MHz.

4.3. Noise performance

4.3.1. Distribution amplifier

In a 50Ω system the distribution amplifier may be used with its input terminated or unterminated. Therefore the noise factor was measured from a 50Ω source with and without a terminating resistor. Both measurements were made at 20 MHz.

Noise factor unterminated = 6·5 dB
Noise factor terminated = 11 dB

4.3.2. Aerial amplifier

As explained in Section 2, the measurement of the noise in the aerial amplifier is given in terms of an output noise factor. This has to be measured with the input to the amplifier terminated in an impedance equivalent to that of the monopole at that frequency. The arrangement for this test is shown in Fig. 10.

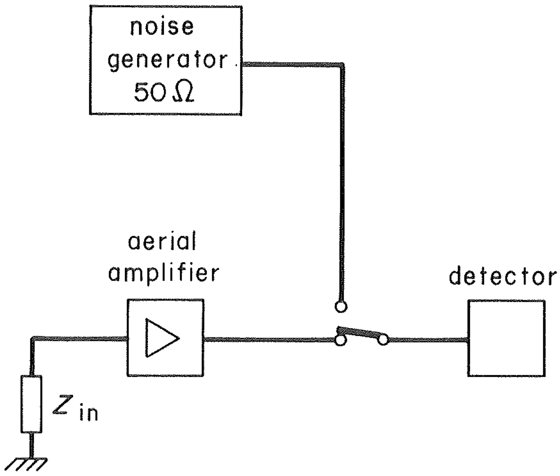

Fig. 10 - Measurement of output noise factor of aerial amplifier

The noise from the amplifier was measured on the detector and the level noted. The noise generator was then switched on and the noise level adjusted until it was the same as the amplifier produced. The generator was calibrated in noise power into 50Ω above thermal noise and therefore it was possible to determine the noise factor directly.

Fig. 11 shows how the output noise factor varies with frequency.

Table 1 shows the values of Z_{in} that were used for the test, these values are equivalent impedances to a 2m monopole at these frequencies.[3]

TABLE 1

Equivalent Z_{in} used in output noise factor test

Frequency	Impedance of 2m monopole	Component used in Z_{in}
30 MHz	20 – j100	20Ω with 56 pf
20 MHz	6 – j350	22 pf
10 MHz	1 – j700	22 pf
3 MHz	0 – j3200	16 pf

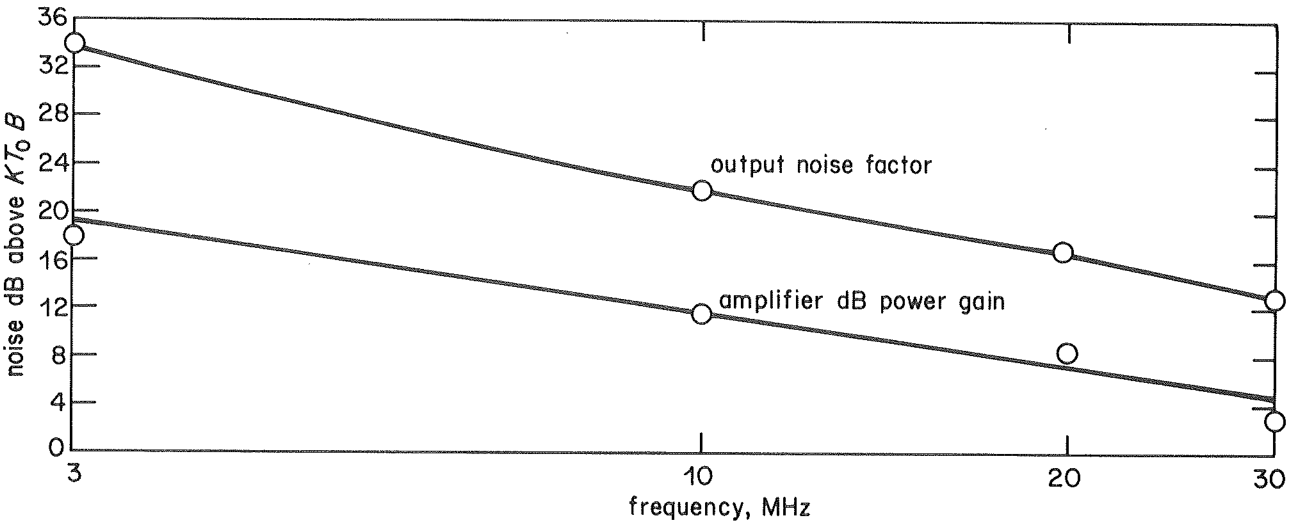

Fig. 11 - Output noise factor v's frequency

Although the amplifier has a voltage gain of approximately unity (see Section 4.5) it has a high power gain. Fig. 11 also shows the power gain of the amplifier with the input terminated by the impedances shown in Table 1. The difference between the two curves on Fig. 11 gives the noise generated by the amplifier. This varies from 16 dB at 3 MHz to 10 dB at 20 MHz relative to KT_0B.

4.4. Frequency response

The aerial amplifier had –3 dB points at 25 kHz and 96 MHz when measured from a 50Ω source. The distribution amplifier measured from a 50Ω source with a 50Ω input terminating resistor had –3 dB points at 25 kHz and 115 MHz.

4.5. Gain

The voltage gain of the amplifier was measured with the input driven from a 50Ω source and the output loaded with 50Ω. Under these conditions the voltage gain is 0·8.

4.6. Power consumption

Both the distribution and aerial amplifiers require a positive voltage supply of 33V. The aerial amplifier takes a current of 60 mA to 90 mA and the distribution amplifier 40 mA to 60 mA. The exact value of current depends on the settings of the bias controls which adjust the linearity of the amplifiers.

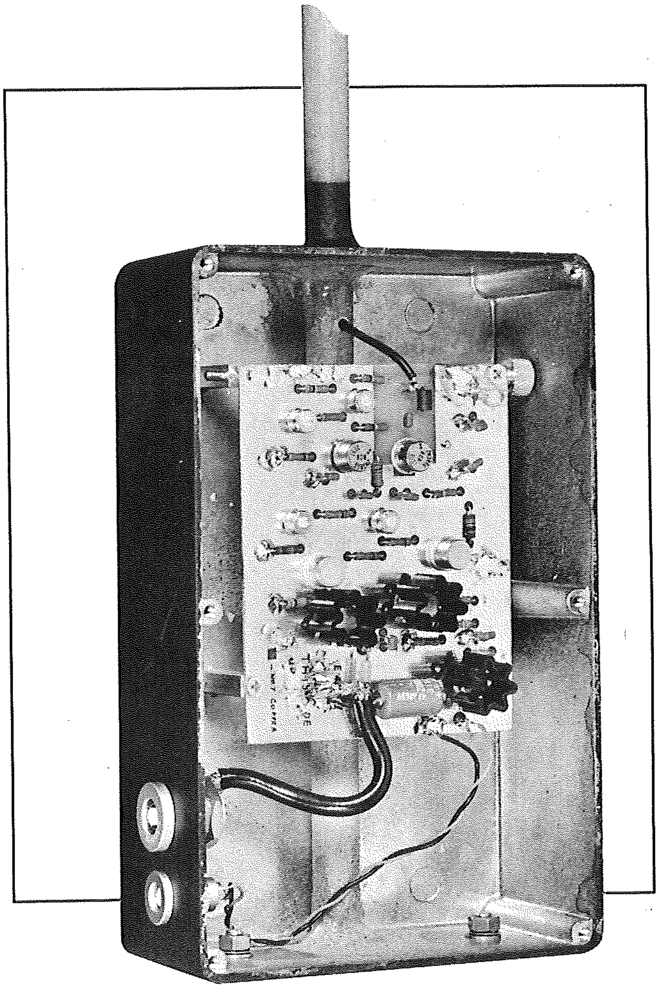

Fig. 12 - Photograph of active aerial

5. Construction of a practical active aerial

A photograph of the active aerial is shown in Fig. 12. The monopole consists of a 2m semi-rigid fibre glass tube with a wire running down its centre. The amplifier is mounted in a water-tight box at the base of the monopole. The box is mounted on an aluminium plate which supports the active aerial when it is in its vertical position.

Because the active aerial may have to work several hundred metres from its power supply an integrated-circuit voltage regulator has been added to each aerial amplifier. The input voltage to the aerial can vary between 35V and 40V and the amplifier supply voltage is kept constant at 33V.

6. Performance of the active aerial

6.1. Equivalent height

The equivalent height of the active aerial can be defined as the height of a vertical monopole that would be required to produce an e.m.f. at its base equal to the output e.m.f. of the amplifier. The e.m.f. produced by a monopole which is short compared to the wavelength at which it is being used is given by

$$\text{e.m.f.} = \tfrac{1}{2} h E \text{ volts}$$

where E is the field in volts/metre
h is the monopole height in metres.

Using this equation for the e.m.f. of a short monopole the active aerial was found to have an equivalent height of 1 m at 1 MHz. The input impedance of the amplifier at this frequency is about 20 kΩ.

6.2. Effect of re-radiation from the active aerial

The effects of re-radiation from the active aerial were investigated using the arrangement shown in Fig. 13. The frequency used for the test was 30 MHz.

One active receiving aerial was kept in a fixed position relative to the transmitting aerial. The amplitude and phase of the signal received were compared with those of the transmitted signal.

Another active aerial was placed 9 metres away from the fixed active aerial and moved towards it in one metre increments. For each position of the movable aerial the phase and amplitude of the signal received on the fixed aerial were noted. These measurements were repeated with the movable aerial's monopole connected to ground by a 50Ω resistor (see Fig. 13). The results of these

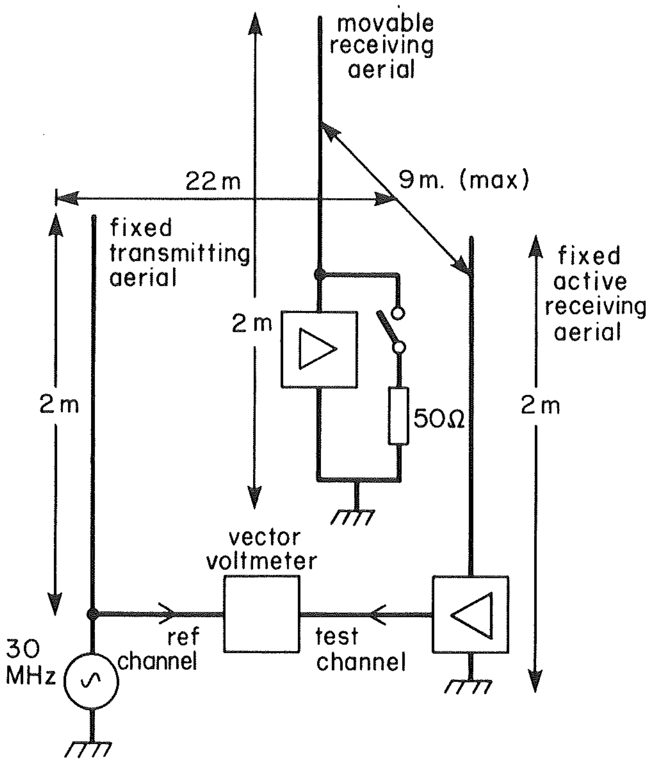

Fig. 13 - Arrangement for re-radiation test

measurements are shown in Figs. 14 and 15. The reference line in both figures shows the phase and amplitude with the movable aerial removed.

At the higher frequencies (30 MHz) a receiving array would need element spacings of between 2 m and 5 m. The effects of re-radiation at these spacings is shown by Figs. 14 and 15 to be particularly severe when 50Ω loaded elements are used.

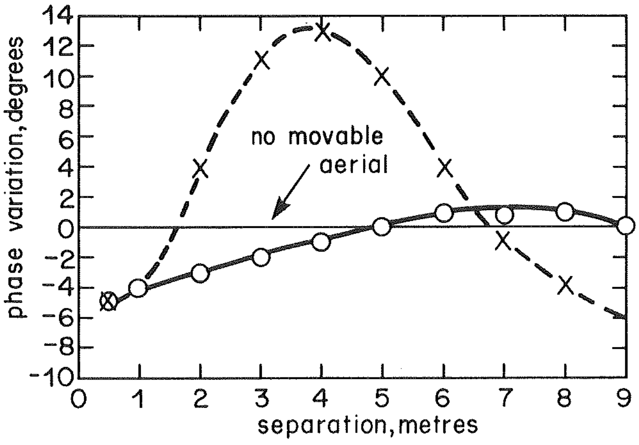

Fig. 14 - Phase variation of received signals v's aerial separation

○———○ Active movable aerial
X — — X 50Ω loaded movable aerial

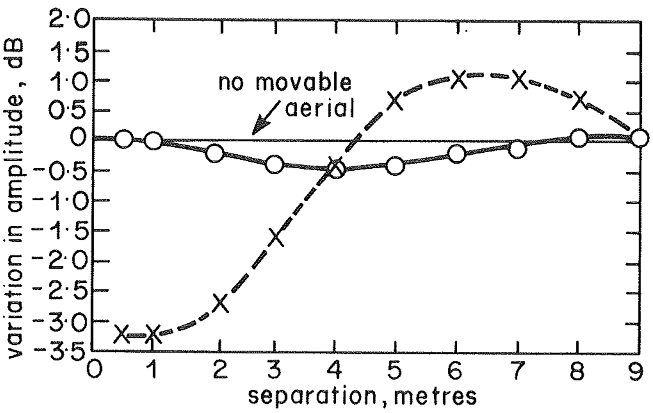

Fig. 15 - Amplitude variation of received signal v's aerial separation

○———○ Active movable aerial
X — — X 50Ω loaded movable aerial

7. Conclusions

An active aerial has been developed which is suitable as an element in an h.f. or m.f. receiving array.

The input impedance of the base amplifier is high and therefore the aerials can be used in a closely spaced array without re-radiation affecting the array pattern. The linearity is adequate for operation under conditions of interference normally encountered at receiving sites.

Experimental arrays are now being planned which will make use of the active aerial and the distribution amplifier. Two forms of array are being considered for construction. Firstly an array which has a steerable horizontal directivity pattern, for use at monitoring stations and, secondly an array which has a vertically steerable pattern for use at overseas receiving sites. Both these arrays will benefit from the fact that the re-radiation effects between elements are negligible so that the radiation pattern can be easily predicted.

8. References

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